Sustainable Grasslands: Resolving Management Options for Livelihood and Environmental Benefits

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ABSTRACT

To help solve the major issues of improving livelihoods and environmental services, grassland research needs to be evaluated within the context of relevant farm systems. Treatments need to show that they not only have significant effects but that they have effects that are meaningful in the context of the relevant farm system. Research often defines an optimum criterion for management that is a single point, but that is difficult to achieve in practice, especially when there are several components in a grassland system that need to be optimised. It is argued that an appropriate criterion for optimising management is a range of values wherein management should aim to maintain the grassland. Typically grasslands comprise many species and appropriate frameworks are needed to determine suitable management practices so that the desirable species dominate. Examples of quantifiable frameworks are presented. A theory of animal production from grassland is then used that shows how optimising stocking rates and then considering the implications can lead to defining managing criteria that create a win-win circumstance for sustaining livestock, household livelihoods and environmental services. Traditionally farmers have thought in terms of the animal carrying capacity on areas of grassland as their main management criteria; which is only a measure of demand. A central component in many relationships is the grassland herbage mass and it is argued that this should be the primary criterion for managing grasslands; herbage mass is a net measure of supply and demand and better links to a wide range of measures of environmental services.

Keywords: Herbage mass, Livestock, Optimal management, Plants, Research strategies, Stocking rates.

Introduction

Grassland ecosystems[1], including natural systems and those resulting from man clearing shrub and woodlands, collectively occupy vast areas of the landscape. About 10% of the world's population depend directly on livestock and grasslands for their livelihoods. Often these are poor communities and ways need to be found to improve household incomes with the resources available. In developed countries the objective is more to optimise financial returns. Because they are such a large part of the landscape, the management of grasslands does have big effects on the environment and the services provided. Mismanaged grasslands can be badly eroded by wind and water, organic carbon stores run down releasing green house gases and productivity decline severely affects many of the world's poor.

During the past century much grassland research focused on managing them to sustain livestock production. Today it is acknowledged that grassland management needs to sustain production, livelihoods and the desired environmental services grasslands provide. Decisions are now more complicated and require a greater understanding of how system

[1] Grassland systems are broadly defined as those areas utilised by grazing herbivores, which includes shrubs and forbs. We include sown pastures and forages within the definition of grasslands. *Grassland* is used to refer to all forage resources.

components interact. Ideally these decisions need to anticipate the impact of management practices and aim to avoid any degradation. It is acknowledged though that farmers are more likely to first make decisions that directly impact on livestock production and then adjust those decisions, based upon how various social and environmental factors may be affected.

Grassland research has often been about designing treatments to understand how the agro-ecosystem functions and, or how best to manage some aspect of the grassland. Results are then analysed and published in terms of the boundaries of the experiments done. Significant treatment effects may not though, be significant enough to be useful for farmers[2]. The conclusions drawn may not align with what is required to achieve sustainable solutions for households, livestock and the environment. To deliver benefits to farmers that sustain grasslands, livelihoods and environmental services, results need to be evaluated against criteria that are appropriate for grassland livestock systems. The implications of better treatments need to be thoroughly explored to identify what other significant components of the system will be affected by applying that treatment. Ultimately farmers are more likely to adopt treatments that are the best compromise to sustain their grasslands, livelihoods (at least in the medium-term) and environmental services. They need to generate incomes, and don't wish to destroy their resource base.

In this paper the objective is to outline some of the ideas developed that are used to analyse research results within the wider context of grassland sustainability. Initially tools that identify better treatments for managing the species within grassland are considered, then how to optimising livestock productivity and also achieve better financial and environmental outcomes. This paper is a companion piece to the chapter (Kemp *et al.*, 2015) in a separate publication prepared for the International Grassland Congress in 2015; with some repetition from that longer paper. The examples used are largely from central NSW and southern regions of Australia. While many of the ideas presented here were developed in Australia and other western economies, this paper is influenced by the authors experience as Editors and frequent reviews of papers plus their experience working in developing countries where a common observation was that grassland scientists in those countries have not had as much exposure to building a research philosophy that is a solid foundation for grassland research.

Manage to an optimum or a range?

The criteria for management of grassland systems has evolved over time. Research into the mechanisms regulating productivity often seek to define an optimum treatment that management should aim for. Typical examples are grassland yield *Vs* fertiliser rate or animal intake *Vs* available green herbage. In both cases the response curve is often hyperbolic *i.e.* an initial steep response that reaches a maximum, beyond which there is no further gain. Researchers often analysed these curves to identify the point at which 95% of the maximum yield was obtained. It was then recommended that farmers manage to that point.

The general sheep or cattle growth response curve to green herbage (Fig. 1) illustrates a typical relationship. The optimum is set where liveweight gain is 90-95% of maximum. That would require continually maintaining the herbage mass around 1.5-2 t DM/ha. Identifying this value is useful for then linking to other criteria but it is almost impossible to exactly maintain in practice.

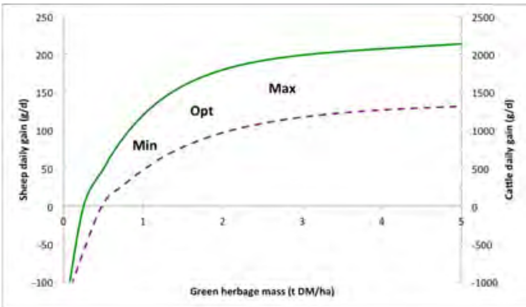


Fig. 1. General relationship for a temperate green grassland and daily gain for meat sheep wethers (50kg, 12 months old – solid line) and for cattle steers (360kg, 24 months – dashed line) derived from Grazfeed (Freer *et al.* 2007). Values for herbage mass to optimise liveweight gain and maximum and minimum values for managing the grassland are shown.

The difficulty is that management to a point isn't always feasible. The variability in climate, soils, animal condition and many other components does mean the current position along the response curve will change and on-farm it isn't feasible to be absolutely precise. This problem becomes more severe when managing within a system that requires a consideration of all the factors that would influence agro-ecosystem functions including relative prices of inputs and outputs, climate, ability to vary livestock numbers and condition and many others. The reality is that it is not practical to manage all components each to their optimum point. The more factors involved the less precision is possible. Ultimately the best that is possible is to try and manage grassland livestock systems to a range of values that overall delivers better outcomes. These considerations lead to the argument that management should aim to satisfy key components with a range of values. That requires knowledge of minimum and maximum values within which the system remains in a sustainable, productive state. The boundaries for management are set such that if the grassland livestock system is maintained within those boundaries it is anticipated that no major adverse effects are likely and over time a near optimum outcome for production, economic and environmental values should be obtained.

Setting the boundary conditions is a different task to optimising components. The range between maximum and minimum values needs to include the optimum for productivity and, or other measures. The objective when setting the range of minimum and maximum values is to identify the limits where management practices need to change to achieve good outcomes. In the example given (Fig. 1) the minimum value set is a herbage mass where daily liveweight gain is 50% of the maximum and the maximum value for management is where it is >95%. As the system being monitored approaches the limits for a component then management needs to change so that the component is restored or maintained within the desired boundaries. In the example (Fig. 1) livestock would be moved from the grassland when the herbage mass is ~1 t DM/ha to enable plants to recover and then grazing would start when the herbage mass approaches ~3t DM/ha. This is what farmers grazing temperate pastures often aim to do. If the stocking rate is set such that the herbage mass remains within these boundaries then there is no need to rotate animals to other grasslands. This is designed to retain species and keep the herbage mass within the boundaries that optimise forage quantity and quality. As a result liveweight gain should be close to the optimum.

At the maximum or minimum boundaries set, productivity or other measures, are unlikely to be optimised perfectly, but if key components are kept within boundaries the system as a whole can be closer to optimal. This apparent imprecision in defining values at which management needs to change, does not mean there is an underlying imprecise relationship. It can be well defined as in Fig. 1. In many cases there is likely to be a well defined response curve between a management practice and the component being monitored. But because that is a curve and a value judgement needs to be made as to where maximum and minimum boundaries should be set, some variation in management practice is a consequence. The net effect when combined across a range of components is that the system boundaries tend to be diffuse and more cloud like than hard and sharp. None of that is a problem if management is maintaining the system within the desired boundaries.

Experience with managing to boundary conditions often identifies that the minimum values for desirable components *e.g.* a key species, herbage mass, forage quality, soil erosion, are generally more important than maximum values. This can simplify the task of identifying when management needs to change to improve the grassland livestock system. For less desirable grassland components the maximum values tolerable are more important for identifying the thresholds to act. Weeds, pests and diseases are likely to have a low maximum value at which intervention is required.

For any grassland livestock system it is important to identify the key components that need to be monitored, to research those factors influencing key components and then to further identify the desired range within which key components need to be managed. Once those criteria are established any experiments then need to be evaluated against them to clearly identify those treatments that are going to be of use to farmers.

Understanding and managing plant species interactions

Grasslands are typically complex mixtures of plant species and a prime management focus of many farmers is to optimise the botanical composition. Even artificial grasslands very quickly comprise several species – those that are sown and natural invaders. Livestock preferentially consume the more desirable species, reducing their competitiveness against invading weeds. Farmers need to manage grasslands in ways that restore the botanical composition to a desirable state. A desirable state is usually one that optimises livestock production and has environmental benefits. The scientific challenge is to find ways of analysing and then managing species mixtures so that there is a high proportion of desirable species (above a minimum) and a low proportion of less-desirable species (below a maximum).

Traditional analyses often investigate how treatments affect each individual species in a grassland. Each species is analysed separately and often independently of other species. Multivariate analyses (more commonly used in Ecology) can identify the main associations between species and the general factors influencing their proportions (Kemp and Dowling, 1991) but those tools don't readily translate to information that can be used by farmers. Qualitative state and transition models were developed to describe the condition of grasslands and the major factors causing transitions between states (Westoby *et al.*, 1989). An important concept coming from this work was that the pathway for degradation in a grassland is mostly different from that for rehabilitation. A quantifiable version of state and transition models, the Pasture Composition Matrix (PCM) was developed so that data could be analysed within a framework of common states and then treatment effects could be mapped on those states (Kemp *et al.*, 1997; Kemp *et al.*, 1998). The PCM was developed for grasslands with a limited range of species groups, rather than multi-layered ecosystems.

Within a grassland it is difficult to properly analyse a mixture of many species when the frequency of a significant proportion of those species can at times be zero. The number of missing values means statistical software can discount a lot of the information. The solution is to allocate species to functional groups, where the eco-physiological similarities between species within a group is greater than between groups. For example: sub-groups of grasses have more within-group similarities than they do with forbs. Functional groups comprise from one to many species; where one species dominates one plant type that can form the group. Using plant functional groups improves the efficiency of analyses and they are more meaningful to farmers than giving them a list of all species. Well-defined plant functional groups can be readily recognised and used to monitor grassland condition.

The more common structure used for a Pasture Composition Matrix analysis is to group species into desirable and less-desirable grasses and relate that ratio to the ratio of desirable to less-desirable forbs (including legumes). In the absence of additional information the division between desirable and less-desirable species can be set at 1:1 *i.e.* when the biomass of desirable species is greater than that of less-desirable the grassland is approaching a desirable state. If there is data available on likely minimum and maximum values for a species then different boundary conditions can be set. In a study investigating the management of *Vulpia* spp. (invasive annual grasses) in a sown grassland of *Phalaris aquatica* (C3 perennial grass) the data indicated that to be competitive *P. aquatica* needed to be a minimum of 60% of the grassland biomass, while the maximum biomass of *Vulpia* spp. (C3 annual grass) should be limited to 12%. A ratio of 5:1 was then appropriate.

A series of five experiments comprising 120 treatments investigated various ways of managing *Vulpia* within an existing *P. aquatica* grassland (Fig. 2). All experiments were adjacent and managed similarly. The treatments compared alone or in combination; grazing, herbicides, fertiliser, hay cuts and other tactics. Analyses of variance identified significant differences among treatments, but not if the results were useful. Applying the data to the Pasture Composition Matrix showed that most treatments did not have any useful benefits. The matrix in this case, compared the log of legumes : other forbs (to allow the ratio to vary from 1:10 to 10:1) against the linear *Phalaris* : *Vulpia* ratio. The grass axis was subdivided at a 5:1 ratio to indicate the desired proportion of grasses on the right-hand side of the graph. The pastures only had a small amount of forbs (*e.g.* thistles) and the second (vertical) axis was dominated by legumes, though some treatments resulted in a dominance of other forbs (broadleaf weeds). The more desired pasture composition is then in the top right-hand quarter of the graph. This matrix efficiently sorted out the valuable treatments, which mostly involved rests from grazing at critical times and showed that while herbicides did control *Vulpia* spp. they also

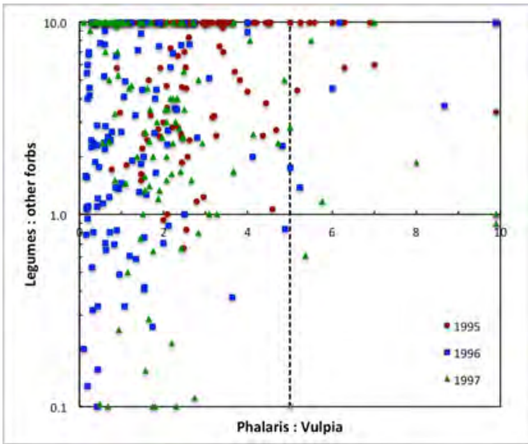


Fig. 2. The effect of 120 treatments across five experiments and three years designed to investigate the management of *Vulpia* spp. within a *P. aquatica* grassland in central NSW, Australia (data from Kemp *et al.* 1998). The central dashed vertical shows a *Phalaris* : *Vulpia* ratio of 5:1.

affected the *Phalaris* and did not achieve a desirable grassland composition (Kemp *et al.*, 1998). This work showed the benefits of analysing all species in combination and in terms that could be readily translated into recommendations for farmers.

Livestock production depends not only on the species in grassland but also on the quantity of edible forage. Management treatments need to identify how best to optimise both species composition and herbage mass. Once the key species, or functional groups, within a grassland are identified, it is possible to evaluate how the proportion of those key species relate to herbage mass. The tool developed to show this is the Pasture Management Envelope (Spain *et al.*, 1985; Kemp *et al.*, 1996). Originally it was developed to help manage field experiments, but the concepts used are relevant to evaluating management practices on farms. The Pasture Management Envelope sets minimum and maximum values for herbage mass and for key species, which creates an 'envelope' wherein the grassland is considered to be in a desired state. As with other techniques it can be more readily understood if annual data is used to check on trends over time. Within season data is variable and can confuse the picture. Ideally data needs to be obtained at times of the year when conditions for grassland growth are reasonably consistent, for example following periods when rainfall is reasonably reliable and temperatures enable growth. As argued earlier the minimum values are more critical and highlight when management needs to change (Kemp *et al.*, 2015).

These tools emphasise that management practices need to always acknowledge that they are affecting two or more components of the grassland and need to be evaluated in that context. Analyses that only examine one component at a time run the real risk of missing important interactions.

What is the optimum stocking rate?

Farmers primarily manage their grasslands for livestock production. Their primary concern is to estimate the carrying capacity or stocking rate of the grassland. What stocking rate achieves the higher net financial return and then what are the implications for the functioning of the grassland and environmental outcomes? Farmers don't want to overuse their resources as that decreases future production as well as having adverse external effects *e.g.* soil erosion by wind or water. Grassland scientists are interested in understanding the same issues. The fundamental relationship of interest is between animal production per head and stocking rate, from which is derived animal production per hectare (Fig. 3).

In Fig. 3 a linear response in production per head is shown. In some instances this can be curved, but the principles considered here still apply. The work done by Jones and Sandland (1974) argued that across many data sets a linear function could apply and other functions might only show marginal statistical gains. Applying Ockham's Razor to the data provides an additional test: the principle states that *among competing hypotheses that predict equally well, the one with the fewest assumptions should be selected*. This principle is a useful guide in science, although acknowledged as not being an absolute truth. An additional scientific issue is that once the relationship between production per head and stocking rate is established, the curve for production per hectare (*i.e.* production per head * stocking rate) is derived from the first fitted curve. These parameters are linked and it is not appropriate to treat them as independent measures. This general model defining the basic animal production relationships has some important implications that help in analysing the system, in providing advice to farmers and for investigating the relationships between animal production on grasslands, grassland condition and environmental effects.

In practice it isn't feasible, nor good financially as discussed below, to manage livestock to achieve the maximum production per ha. More realistically farmers can aim for 75% of maximum production per ha, but there are two points (A, B) where that occurs with very different effects on productivity per head. Animals stocked at point A are producing at 75% of their potential per head and those at point B only 25%. That means animals at point A would grow to a target (market) weight in one-third of the time of those at point B. These affects are summarised in Table 1 along with several other associated factors that will vary between points A and B.

The peak of the production per ha curve (Fig. 3) is the biological optimum, but that is not the financial optimum; the literature often confuses these optima. At the peak of the per ha curve the marginal gain per ha (slope) for an additional 'animal' is zero; the additional cost of adding an extra animal is not rewarded with any gain in productivity per ha and thence per farm. Financial analyses tend to

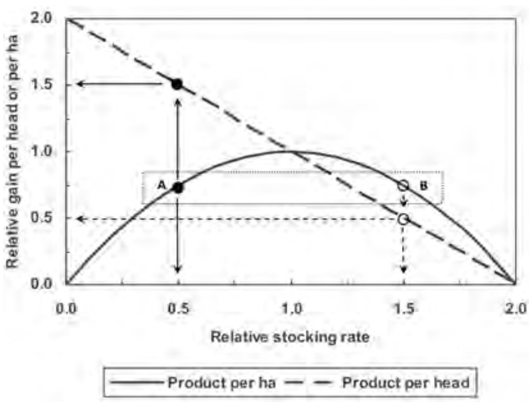


Fig. 3. Basic relationships between stocking rate and animal production. Points A and B are where production per hectare is 0.75 of the biological optimum. The dashed line is y = 2-x and the solid line y = (2-x).x (Jones and Sandland 1974).

show that the optimum economic stocking rate is likely to be around 75% of the maximum production per ha (point A Fig. 3); the actual point depends upon relative prices. The mathematics underlying these general curves mean that when production per ha is 75% of the biological maximum per ha the stocking rate is 50% of the stocking rate at the biological maximum and one-third that at point B. These large differences in per head production provide the clues that researchers, farmers and their advisors can use to determine how close they are to the likely financial optimum. Experiments need to consider such frameworks when evaluating the results obtained. Often experiments investigate treatments around point A, but if the model considered here is used, estimates of where point B is can be made.

There are many other implications (Table 1) that arise from considering the management of livestock at points A or B (Fig. 3). Optimum net profit is achieved around point A, while a net financial loss can occur at point B, depending upon the costs involved. The management risks at point B are much greater as there is a reduced buffer in forage reserves and animal condition, more likelihood of animal losses in periods of drought or other climatic stresses – again related to a poorer animal condition, more labour costs to manage three-times the number of animals, more likelihood of having to re-sow grasslands and higher supplementary fodder costs – as less forage is available, all at point B. When managing livestock around point B and climatic conditions for grassland growth decline, then animals reduce growth rates and can reach the point where they lose weight. If the animals lose weight then the stocking rate should be reduced by 75% to reach point A and restore productivity to the level that is appropriate for the system at that time. It may not always be feasible to restore productivity

Table 1. Comparison of managing grassland at points above and below the biological optimum to achieve 0.75 of the maximum productivity in animal gain per hectare (Fig. 3). Approximate levels of various factors are rated, along with the relative advantage / disadvantage of managing to point A or point B. The more +/- symbols the greater the response. (Kemp and Michalk, 2007)

Measure	Point A	Point B	A / B
	Relative to values at biologically optimal stocking rate		
Animal gain/ha	0.75	0.75	1
Stocking rate	0.50	1.50	0.33
Animal gain/head	1.50	0.50	3.0
Time to reach market weights	0.67	2.00	0.33
Implications			
Net profit	high	low	++
Management risk and uncertainty	less	more	++
Carry-over to off-season	more	less	+++
Drought impact	less	more	++
Labour requirement	less	more	++
Need to resow grasslands	less	more	++
Cost of supplementary feed	low	high	++
Herbage mass/ha	*high*	*low*	+++
Palatable grass content	*high*	*low*	++
Forage quality	*lower*	*moderate*	-
Weed risk	*low*	*high*	++
Biodiversity	*stable*	*less*	+
Soil erosion risk	low	high	++
Water management	good	risky	++
Nutrient loss	low	high	++
Fertiliser need	low	high	++

to a high level, but these relationships indicate how much change is required.

The logic of the effects predicted with this simple model has been evident in Australia in times of drought. Farmers used to only make small reductions in stocking rates as droughts commenced, even though animal growth rates were close to zero. Then they needed to purchase fodder early as the drought proceeded, resulting in large numbers of animals in poor condition that could not be sold and a high total cost for fodder. In more recent droughts farmers destocked early, selling a much higher proportion of their flocks and herds, saving on fodder costs and as they then have more forage on the grasslands the need to purchase any fodder is lessened.

Stocking rates and grassland condition

Once the financially optimal stocking rate has been decided, it is then important to consider what that means for various other components of the grassland livestock production system. Animals at points A and B are growing at different rates and the implication from that is they have access to more forage and thus total nutrients, at A compared to B. A general indication of what this may tell us about the amount of forage available can be assessed by considering the known relationship between animal growth and nutrient supply, which is approximated by animal growth rates in relation to herbage mass per ha (Fig. 4); we are considering here the available metabolisable energy as indicated by the amount of green forage. The green component of herbage mass is the main driver of animal productivity. These examples assume an actively growing grassland such as *Lolium perenne* in a vegetative state.

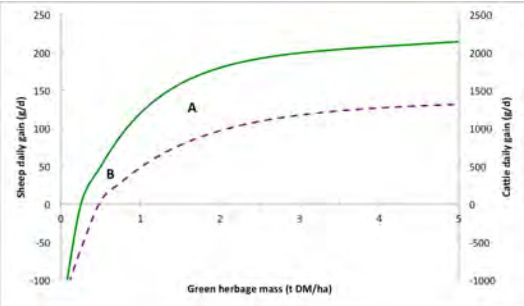
On Fig. 4 The points A and B relate to those on Fig. 3 where production per head is 75% or 25% of maximum daily gain (respectively) both resulting in 75% of the maximum production per ha. Point A for young growing sheep is a green herbage mass of 1.5 t DM/ha while for young growing cattle this is 2 t DM/ha. Point B for sheep is 0.5 t DM/ha and for cattle 0.75 t DM/ha. It is important to emphasise that this is green vegetative, herbage and not total. Below around 0.5 t DM/ha both sheep and cattle can lose weight as their intake can drop to maintenance levels or lower. To then maintain sheep and cattle in their most productive state requires a grassland of green forage averaging around 2 t DM/ha.

Maintaining the green herbage around 2 t DM/ha has implications for the grassland growth rate (Fig. 5). At point A the growth rate for an actively growing temperate grassland is near the maximum. At point B the growth rate is only about half that at point A. If the stocking rate is maintained at the lower values this then means that over the growing season, the total herbage mass produced doubles compared to areas maintained at point B. Considerable benefits then flow from using a lower stocking rate. Many regions have growing and non-growing seasons and it is important to carry over more forage wherever possible. Having greater standing forage reserves means that animals can be better fed in short-term droughts or cold seasons and the amount of purchased feed required is significantly reduced. There is less management risk for livestock as they will be in better condition and for the grasslands as the possibility of over-utilising the available forage is less.

Maintaining a higher level of herbage mass on grasslands helps to keep it in a more productive and sustainable state. Using the above notional data, if the stocking rate at A is one-third that at B (Fig. 3) while the pasture growth rate and total herbage produced at A is twice that at B (Fig. 5) then the forage allowance per animal at A is six times that of B. This indicates a significant reduction in utilisation rate, which means less grazing pressure on desirable species thereby increasing their ability to compete against less-desirable weeds. A lower level of utilisation is often necessary to sustain permanent grasslands. The economic advantage is then a reduced requirement to resow grasslands. This discussion identifies the need to on-average maintain lower stocking rates and a higher herbage mass. When reviewing research results where do they fit within this framework?

Stocking rates, biodiversity, soil loss, water and nutrients

The implications of maintaining a moderate, financially optimal, stocking rate and a higher on-average herbage mass when grazing grasslands, extends to several environmental values. Managing the stocking rate at point A creates a win-win situation for several other important environmental system components. Research into the biodiversity of grasslands across southern Australia (Kemp *et al.*, 2003) found that these optimal conditions identified above maintained native grass species and invertebrates. Soil water runoff was minimized when the herbage mass was > 2t DM /ha (Hughes *et al.*, 2006) which greatly reduced any soil and nutrient losses. If runoff



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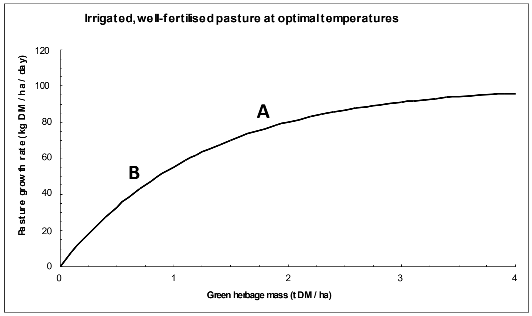

Fig. 5. Average relationship between temperate green herbage mass and daily pasture growth rates. The points A and B relate to those in Fig. 3.

is reduced then infiltration must increase, resulting in further gains in grassland growth rates from more water in the soil. It would be expected that with less animals per ha and better grassland condition the need to apply fertiliser would be reduced, as the average utilisation level is less.

Social implications

Resolving the stocking rate that optimises financial returns is designed to improve household incomes. Achieving better financial returns from fewer livestock has additional social implications. The need for labour is less (point A *Vs* B) allowing in developing countries, children to attend school, family members to manage the livestock and obtain off-farm income and a more secure farm business. As the grassland would be in better condition, the wider community would exert less pressure on farmers to change practices and, or increase regulation.

Is stocking rate the better criterion?

The above discussion used stocking rate as the primary criterion for determining animal numbers, grassland utilisation and impact on environmental variables. But stocking rate only reflects demand, while there will be a range of other factors affecting the supply of herbage from grassland. Thus in practice the stocking rate needs to be continually adjusted to optimise productivity and the other system components. The standing herbage mass better reflects the balance between supply and demand for forage. Many of the other system components, as well as animal production, are related to grassland herbage mass. Once the optimum range within which herbage mass should be managed is known, then it can be a more useful criterion to sustain animal productivity and the other system components. Often grasslands are grazed in rotation, and farmers do start and stop grazing a field based on the herbage mass available. This is the oldest grassland management technique used, having been done since man first domesticated livestock. Today though we have much better ideas about the level of herbage mass to maintain.

It is therefore proposed that to manage grasslands sustainably, herbage mass needs to continue to be used as the key management criterion. Research needs to refine the range for herbage mass that sustains the grasslands, optimises incomes and maintains the environmental services provided by grasslands.

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